ADVANCED STEAM GENERATORS

Geo. A. Richards (george.richards@netl.doe.gov, 304-285-4458)
Kent H. Casleton (kent.casleton@netl.doe.gov, 304-285-4573)
Robie E. Lewis (robie.lewis@netl.doe.gov, 304-285-4445)
William A. Rogers (william.rogers@netl.doe.gov, 304-285-4272)
National Energy Technology Laboratory
3601 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

Mark R. Woike (Mark.R.Woike@grc.nasa.gov, 419-621-3379)
Brian P. Willis (Brian.P.Willis@grc.nasa.gov, 419-621-3202)
NASA Glenn Research Center
Plumb Brook Station
6100 Columbus Avenue
Sandusky, OH 44870

Introduction

Concerns about climate change have encouraged significant interest in concepts for ultra-low or "zero"-emissions power generation systems. In some proposed concepts, nitrogen is removed from the combustion air and replaced with another diluent such as carbon dioxide or steam. In this way, formation of nitrogen oxides is prevented, and the exhaust stream can be separated into concentrated CO_2 and steam or water streams. The concentrated CO_2 stream could then serve as input to a CO_2 sequestration process or utilized in some other way. Some of these concepts are illustrated in Figure 1.

This project is an investigation of one approach to "zero" emission power generation. Oxy-fuel combustion is used with steam as diluent in a power cycle proposed by Clean Energy Systems, Inc. (CES) [1,2]. In oxy-fuel combustion, air separation is used to produce nearly pure oxygen for combustion. In this particular concept, the combustion temperatures are moderated by steam as a diluent. An advantage of this technique is that water in the product stream can be condensed with relative ease, leaving a pure CO_2 stream suitable for sequestration. Because most of the atmospheric nitrogen has been separated from the oxidant, the potential to form any NOx pollutant is very small. Trace quantities of any minor pollutants species that do form are captured with the CO_2 or can be readily removed from the condensate. The result is a nearly zero-emission power plant.

A sketch of the turbine system proposed by CES is shown in Figure 2. NETL is working with CES to develop a reheat combustor for this application. The reheat combustion application is unusual even among oxy-fuel combustion applications. Most often, oxy-fuel combustion is carried out with the intent of producing very high

temperatures for heat transfer to a product. In the reheat case, incoming steam is mixed with the oxygen and natural gas fuel to 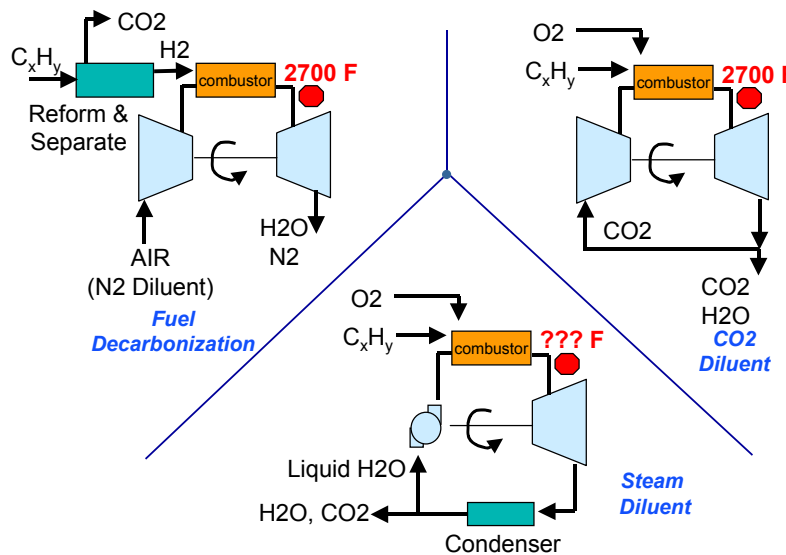control the temperature of the output stream to about 1480 K. A potential concern is the possibility of quenching non-equilibrium levels of CO or unburned fuel in the mixing process. Inadequate residence times in the combustor and/or slow kinetics could possibly result in unacceptably high emissions. Thus, the reheat combustor design must balance the need for minimal excess oxygen with the need to oxidize the CO. This paper will describe the progress made to date in the design, fabrication, and simulation of a reheat combustor for an advanced steam generator system, and discuss planned experimental testing to be conducted in conjunction with NASA Glenn Research Center-Plumb Brook Station.

Figure 1. Selected power cycles that produce concentrated CO_2 streams

Cycle description:

In the CES concept, oxygen and natural gas are burned in a "gas generator", and enough water or steam is added in the gas generator to produce an exhaust stream that has appropriate pressure and temperature for the high-pressure (HP) turbine. Operating conditions and a conceptual design of the oxy-fuel gas generator in Figure 2 have been proposed by Anderson et al. [1]. To achieve high efficiency, the product stream exits the HP turbine and enters a "reheater" where natural gas and oxygen are added to

Figure 2. Steam diluent arrangement proposed by Clean Energy Systems, Inc.

raise the product temperature before continuing with further expansion. As in a conventional steam power plant, the reheat process allows expansion from high-pressure conditions needed for efficiency, without compromising steam quality during the low-pressure expansion. The values of temperature and pressure before and after the reheater shown on Figure 2 are expected to be of interest to the design proposed by Anderson [1]. To date, there are no published reports on how to design a combustor to produce the reheat conditions proposed in Figure 2.

Proper design of the reheater is critical. Use of excess O_2 wastes costly air separation capability and adds to the load to the condenser, and excess fuel will produce fuel in the CO_2 product. In addition the staging of the steam diluent addition requires careful analysis. Too little steam added could lead to excessive temperature excursions and high equilibrium levels of CO, while excessive steam addition could over-quench the combustion products and slow the oxidation rate of CO to CO_2.
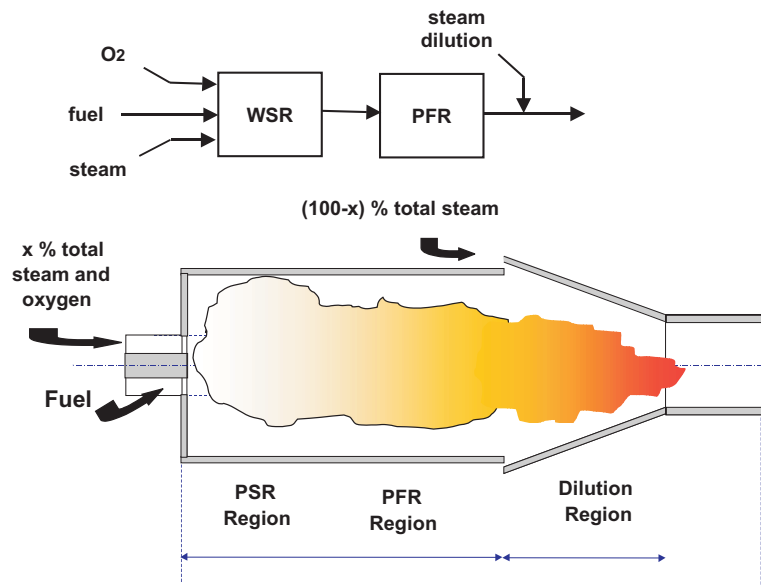

Figure 3. Simple well-stirred reactor/plug-flow reactor network combination to represent a turbine combustor

For this reason, the detailed chemical kinetics of this concept have been investigated, focusing primarily on CO levels and effects of residence time. The combination of a well-stirred reactor followed by a plug-flow reactor has been utilized as a simplified approach to focus on the chemical kinetic effects. Results are used to guide more detailed CFD studies of possible combustor designs. Ultimately, these simulations are used to develop a more detailed design of a test combustor for subsequent experimental studies.

A simple reactor network is used to represent the turbine combustor. A well-stirred reactor (WSR) representing the mixing/primary zone of the combustor is followed by a plug flow reactor (PFR). The PFR simulates the burnout zone/ intermediate zone where the final oxidation occurs. A quench zone tailors the final exit temperature to the specified value of 1480K (2200 F). This is illustrated in Figure 3.

The Chemkin-II [3] package is used to perform these simulations. Chemical kinetic information is supplied in a chemical reaction mechanism provided by the user. In this case, the methane combustion chemistry is modeled by means of the GRI-Mech 3.0 chemical kinetic mechanism [4].

Designing the Reheat Combustor

The reheat combustor is modeled as a well-stirred reactor (WSR) and a plug flow reactor (PFR) in series (see Fig. 2). WSR calculations were performed for equivalence ratios (ϕ) of 0.9 and 1.0 for residence times of 20 and 40 ms, examining parameters such as outlet temperature and CO concentrations with variation of the H_2O/O_2 molar ratio ("dilution ratio"). Based on these results, particular operating points were selected for PFR calculations to assess relative CO burnout times.

Although, not shown here, it was found that exit temperatures were in the range of 2200 to 2300 K for low values of added steam ($[H_2O]/[O_2] = 3$) and decreased monotonically to about 1500 K for $[H_2O]/[O_2] \sim 7.5$. Since this is close to the exit temperature of the reheat combustor assumed for this cycle, this represents an approximate maximum value for the steam diluent.
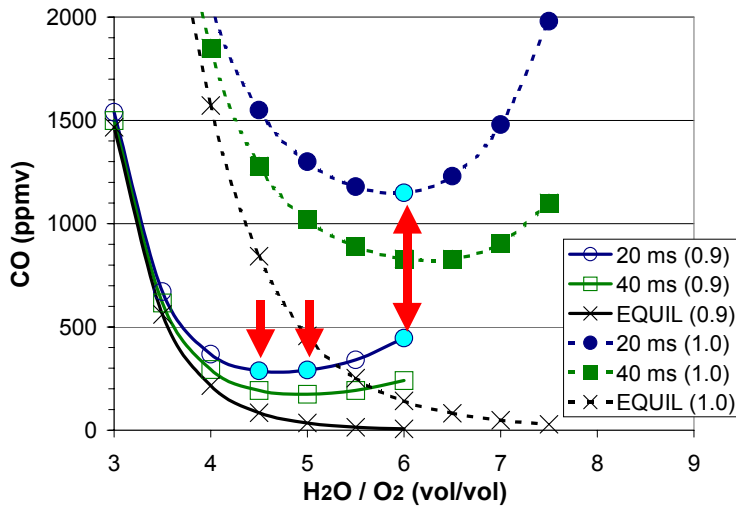

Figure 4. CO emissions at WSR exit

Figure 4 shows the calculated CO concentrations at the exit of the WSR for equivalence ratios (ϕ) of 0.9 and 1.0 and residence times (τ) of 20 and 40 ms. Typically, the plot of CO versus $[H_2O]/[O_2]$ is "U"-shaped. The CO is quite high at low diluent levels, corresponding to high exit temperatures and high equilibrium concentrations. As the diluent is increased, the CO goes through a minimum and then increases rapidly. This rapid increase at high $[H_2O]/[O_2]$ values is likely due to the much lower exit temperature and its negative impact on the CO oxidation rate. Consistent with this, the CO at the WSR exhaust is reduced substantially as the residence time is increased.

Based on these WSR results, four conditions were chosen for plug flow reactor (PFR) calculations. Figure 5 shows the CO burnout for $\tau=20$ and $[H_2O]/[O_2] = 6$ for both

ϕ=0.9 and 1.0. In addition, operating points with ϕ=0.9 and τ=20 ms for $[H_2O]/[O_2]$ = 4.5 and 5 were also examined. These operating points are indicated by the red arrows in Figure 4.
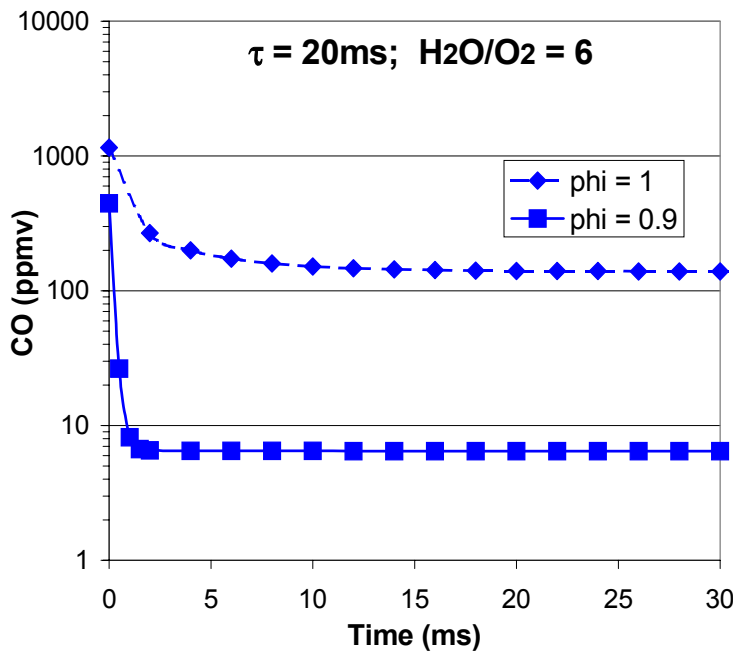

Figure 5. CO levels at PFR exit for WSR operation at τ = 20 ms and H_2O/O_2 =6

- **Stirred and plug flow geometry (WSR & PFR) set for generous 20 ms residence times.**
- **WSR steam flow at minimum of CO curves (80/20 split).**
- **Conventional swirl inlet with diffusion flame stabilization.**
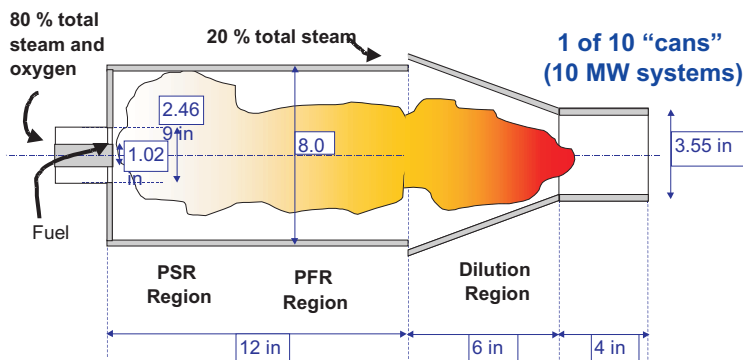- **Oxygen premixed with steam inlet to WSR (quasi-air!).**

Figure 6. Designing the Reheat Combustor

These results demonstrate that, for the various operating conditions examined, equilibrium CO levels can be attained within 5 to 10 ms in the PFR burnout stage. Excess oxygen levels (i.e. equivalence ratio) has significant effect on the time scales required for CO burnout, amounting to one to two orders of magnitude difference when comparing ϕ = 0.9 and 1.0. Process economics will require minimal excess oxygen, while achieving adequate CO emissions performance will necessitate some level of excess oxygen. These results are discussed in more detail by Lewis et al. [5].

In summary, the kinetic modeling suggests that allowing 20 ms residence times for both the well-stirred reactor and the plug-flow reactor regions should be ample to provide adequate CO burnout in the reheat combustor.

Furthermore, Figure 4 can be used to estimate the split in steam diluent between the primary zone and the dilution section.

- **Mixture fraction model, FLUENT**
- **Mixing design achieves design goals: exit is near equilibrium product composition.**
- **Similar results for 75% and 50 % load cases.**
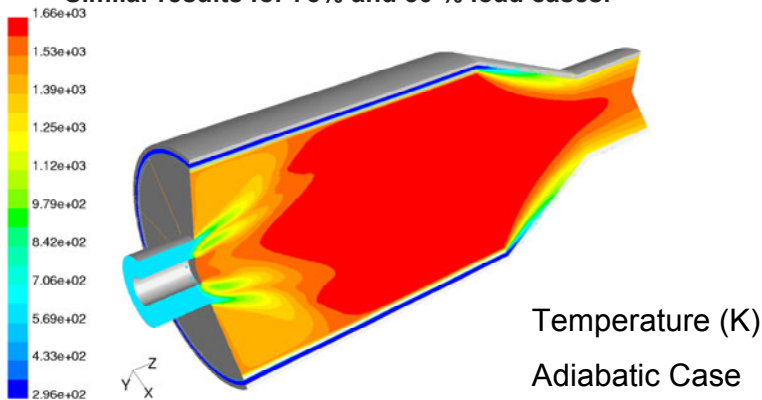

Temperature (K)

Adiabatic Case

Figure 7. CFD Simulation of Base Design

As discussed above, at equilibrium, the exit temperature of the well-stirred reactor falls to about 1480 K for steam-to-oxygen dilution ratios of about 7.5-8. Analyses of the WSR/PFR combination indicated an optimal steam-to-oxygen dilution ratio of about 6 or about 80% of the maximum steam flow. The remaining 20% steam can be used in the dilution zone to produce the desired exit temperature of 1480 K. These results are summarized in Figure 6.

Based on these results, a conceptual design of the reheat combustor has been completed and CFD simulations of that design have been performed. An example of those simulation results is shown in Figure 7. Using these simulation and design tools, the design of the reheat combustor has been completed, and hardware is being fabricated for testing later in FY02. A schematic drawing of the reheater test hardware is shown in Figure 8.

- **Design of test facility hardware is in progress**
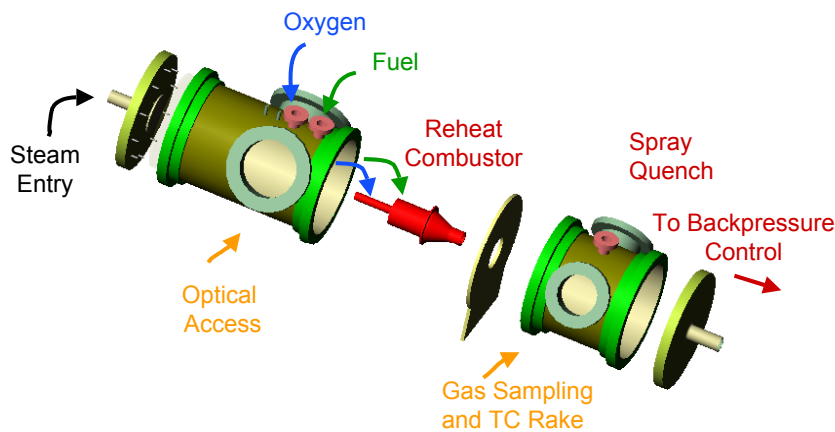- **Tests planned at full/part load conditions**

Figure 8. Schematic drawing of reheater test hardware

Future Activities

As discussed above, NETL plans to test the reheat combustor hardware under realistic conditions during FY02. NETL and NASA-Glenn Research Center will collaborate on this testing, utilizing the Hypersonic Tunnel Facility Complex at NASA-GRC/Plum Brook Station. This facility has extensive infrastructure (oxygen, nitrogen, natural gas, CO_2, and steam at appropriate conditions) in place to support the proposed test program.   The goal of these tests is to confirm the expected performance of the proposed design at representative scale.

References:

1. Anderson, R., Brandt, H., Mueggenburg, H., Taylor, J., Viteri, F. (1998). A Power Plant Concept Which Minimizes the Cost of Carbon Dioxide Sequestration and Eliminates the Emission of Atmospheric Pollutants, 4th International Conference On Greenhouse Gas Control Technologies, August 30 – September 2, Interlaken, Switzerland.

2. Bilger, R. W., (1999). Zero Release Combustion Technologies and the Oxygen Economy, The Fifth International Conference on Technologies and Combustion for a Clean Environment, Lisbon, Portugal, 12- 15 July, 1999.

3. Kee, R. J., Rupley, F. M., and Miller, J. A. (1989). "Chemkin-II: A Fortran Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics," Sandia National Laboratory Report SAND89-8009.

4. Smith, G. P., Golden, D. M., Frenklach, M., Moriarty, N. W., Eiteneer, B., Goldenberg, M., Bowman, C. T., Hanson, R. K., Song, S., Gardiner, W. C., Jr., Lissianski, V. V., and Qin, Z., http://www.me.berkeley.edu/gri_mech/

5. Lewis, R. E., Casleton, K. H., Richards, G. A., Straub, D. L., and Rogers, W. A. (2001). A Comparison of Turbine Combustion Concepts Suitable for Integration with CO_2 Sequestration, 2001 Joint International Combustion Symposium, Kauai, HI, September 10-12, 2001.